

High frequency observations of southern pulsars

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ABSTRACT

We present polarization data for 32 mainly southern pulsars at 8.4 GHz. The observations show that the polarization fraction is low in most pulsars at this frequency except for the young, energetic pulsars which continue to show polarization fractions in excess of 60 per cent. All the pulsars in the sample show evidence for conal emission with only one third also showing core emission. Many profiles are asymmetric, with either the leading or the trailing part of cone not detectable. Somewhat surprisingly, the asymmetric profiles tend to be more polarized than the symmetrical profiles. Little or no pulse narrowing is seen between 1 and 8.4 GHz. The spectral behaviour of the orthogonal polarization modes and radius to frequency mapping can likely account for much of the observational phenomenology. Highly polarized components may originate from higher in the magnetosphere than unpolarized components.

Key words: pulsars:general

1 INTRODUCTION

It is generally accepted that low frequency radio emission from pulsars arises from further out the magnetosphere than high frequency emission. The fact that the open magnetic field lines diverge outwards at higher altitudes then implies that low frequency profiles are generally broader than those at high frequency. However, this broadening effect is most prominent at frequencies below about 1 GHz. Above this frequency, the profile narrows only slowly (if at all) as pointed out by von Hoensbroech & Xilouris (1997) in their high frequency study. Both Mitra & Rankin (2001) and Gangadhara & Gupta (2003) showed that emission appears not to occur throughout the polar cap but is concentrated in the inner ~ 60 per cent, again limiting the amount of observational widening seen.

Observationally, individual components within a pulse profile can be classified as ‘core’ or ‘cone’ components (Rankin 1983; Lyne & Manchester 1988; Rankin 1990). Core emission arises from near the magnetic axis whereas cone emission originates from more distant regions of the magnetosphere. There appears to be a difference in the spectral index of core and cone emission with core emission having the steeper index. Theoretical considerations show that these differences are perhaps caused by refraction in the magnetosphere, where the lower plasma density in the central (core) regions cause enhanced refraction and effectively a steeper spectral index (Petrova 2002). The observational implications are that low frequency profiles can often be dominated by core emission whereas at high frequencies,

prominent conal outriders can often be detected. However, it is not clear cut that two different emission mechanisms operate. Kramer et al. (1994) and Sieber (1997) showed that a number of the observational effects could be attributed to geometric arguments and Lyne & Manchester (1988) prefer a patchy beam model. von Hoensbroech et al. (1998) also showed that there exists a ‘class’ of pulsars which has one highly polarized component usually on the extreme leading or trailing edge of the profile. The highly polarized component has a flat spectral index and is therefore prominent at high frequencies. The presence of dominant outrider components at high frequencies compared to low frequencies can actually *increase* the pulse width and some care must be taken when comparing results at different frequencies.

In general, the fractional linear polarization decreases with increasing frequency. Competition between orthogonal polarization modes has been shown to result in such an effect (e.g. Karastergiou et al. 2002). The steep decrease in fractional linear polarization seen in some pulsars at very high frequencies (above ~ 10 GHz) may warrant an alternative explanation (Xilouris et al. 1996). In any case, young pulsars form a special group by retaining their high fractional polarization over a wide frequency range. In some pulsars, the high linear polarization seen at low frequencies decreases, while at the same time the circular polarization increases. These are observational examples of the ‘conversion’ of linear to circular polarization discussed by von Hoensbroech & Lesch (1999). The position angle swing is generally expected to have its largest slope at the longitude at which the line of sight crosses the magnetic meridian.

Core components therefore tend to have steep PA swings across them, whereas conal components show only shallow PA swings. Core components sometimes also show a swing in the sign of the circular polarization; this is rarely observed in conal components.

It is worth noting that single-pulse studies reveal a different side of pulsar emission relating to short timescale changes in the pulsar magnetosphere. Integrated profiles and single pulses often show important observational differences. For example, the spectral index measured in single pulses does not necessarily show the same dependence on the type of component (Kramer et al. 2003) as discussed above. Also, in the single pulses a variety of polarization phenomena are observed, such as swings in the sign of the circular polarization in cone components (Karastergiou et al. 2001), which disappear in the averaging process (Karastergiou et al. 2003).

This paper is the fourth in a series of recent papers examining high frequency polarization of integrated profiles of southern pulsars. In the first paper Karastergiou, Johnston & Manchester (2005; hereafter KJM05) observed 48 pulsars at 3.1 GHz and considered the polarization evolution with frequency in the context of competing orthogonal modes. They developed an empirical model for the frequency evolution of the linear polarization based on different spectral indices of the orthogonally polarized modes. In the second paper, Karastergiou & Johnston (2006; hereafter KJ06) concentrated on 17 strong pulsars at both 1.4 and 3.1 GHz and made a careful comparison of the position angle (PA) swing at the two frequencies. Finally, Johnston & Weisberg (2006) looked at the morphology and polarization of a group of 14 young pulsars and showed that emission arises from high in the magnetosphere with little or no core emission and highly polarized conal emission.

In this paper we examine a group of the strongest pulsars at 8.4 GHz in order to study the total intensity profile and polarization. We use previous observations of these pulsars made at lower frequencies to draw conclusions on the frequency evolution of these properties. Apart from a small number of isolated exceptions, these are the first observations of these pulsars above 3 GHz and the first systematic study of southern pulsars at high frequencies.

2 OBSERVATIONS

Observations were carried out using the 64-m radio telescope located near Parkes, New South Wales. The central frequency was 8.356 GHz with a total bandwidth of 512 MHz. The feed consists of dual circular receptors and a calibrator probe at 45 degrees to the feed probes. During the observing run, observations were made of the flux calibrator Hydra A whose flux density is 8.5 Jy at this frequency. This allowed us to determine the system equivalent flux density to be 48 Jy.

The pulsars were typically observed for 30 mins each, preceded by a 2 min observation of a pulsed calibrator signal. The total bandwidth was subdivided into 1024 frequency channels and the pulsar period divided into 1024 phase bins by the backend correlator. The correlator folds the data for 60 s at the topocentric period of the pulsar at that epoch and records the data to disk for offline-processing.

The data were taken in two periods. The first ran from 2005 May 4 to 2005 May 10. Unfortunately many of the resultant pulse profiles were ruined by systematic problems in the backend system. Although the total intensity and circular polarization profiles were generally reasonable the Stokes Q and U profiles were completely corrupted. However, the data were useful in that we were able to determine which pulsars showed good signal to noise in 30 min and which were undetectable. We obtained additional time between 2005 July 8 and July 12 and re-observed 32 pulsars for which we had convincing detections from the earlier session.

The data were analysed off-line using the PSRCHIVE software package (Hotan et al. 2004). Polarization calibration was carried out using the observations of the pulsed calibrator signal to determine the relative gain and phase between the two feed probes. The data were corrected for parallactic angle and the orientation of the feed. The position angles were also corrected for Faraday rotation through the interstellar medium using the nominal rotation measure (at this high frequency errors in the rotation measure make very little impact on the absolute position angles). Flux calibration was carried out using the Hydra A observations. The final product was therefore flux and polarization calibrated Stokes I , Q , U , V profiles.

3 CATEGORISING THE PROFILES

The classification of pulsars into categories based on their observational properties is a natural step in attempting to understand the underlying physics. Rankin (1983) is a pioneer in this field and her subsequent papers lay out a series of ground rules for the classification of pulse profiles at frequencies around ~ 1 GHz. However, not only are useful criteria for the classification difficult to decide upon, it is also often hard to unambiguously identify individual components within a complex pulse morphology, especially when the components have different frequency dependent behaviour. In this section we outline a scheme for classifying pulsars at this high frequency of 8.4 GHz.

By and large, virtually all pulsars at 8.4 GHz show conal emission of some sort and we should not expect any core only pulsars. This is not overly surprising. Core dominated pulsars are likely to be steep spectrum objects and therefore not above our detection threshold limit. Secondly conal emission has a flatter spectral index and is more likely to be seen at higher frequencies. We therefore introduce two broad categories. The first contains pulsars in which only conal emission is present and the second contains pulsars for which both core and cone emission can be seen. Each of these categories has a number of sub-classes based on the degree of symmetry of the profile.

3.1 Profiles without core emission

3.1.1 Symmetric cone distribution

Profiles in this category are those with no evident central component at any frequency and with a symmetric (and perhaps multiple) distribution of cones. The polarization tends to be low and decreases further with increasing frequency.

Table 1. The observed pulsars and their parameters. Numbers in brackets denote the value for the interpulses. Values for percentage linear (%L) and circular (%V) refer to the entire profile; individual components can differ significantly from this.

Jname	Bname	Period (ms)	Age (Myr)	S _{8.4} (mJy)	W ₁₀ (deg)	%L	%V
J0630–2834	B0628–26	1244.4	2.77	2.3	20	<7	<7
J0659+1414	B0656+14	384.9	0.11	2.5	26	<7	<7
J0738–4042	B0736–40	374.9	3.7	7.0	24	11±2	3±2
J0742–2822	B0738–28	166.8	0.16	1.6	14	57±4	–14±4
J0835–4510	B0833–45	89.3	0.011	4.1	18	80±1	–27±1
J0837–4135	B0835–41	751.6	3.4	1.3	13	15±3	–6±3
J0908–4913	B0906–49	106.8	0.11	0.4(1.2)	15(10)	75±4(71±1)	<4(–15±1)
J0922+0638	B0919+06	430.6	0.50	0.6	7	15±12	<12
J0953+0755	B0950+08	253.1	17.5	4.3	30	<4	<4
J1048–5832	B1046–58	123.7	0.020	3.2	19	78±1	19±1
J1056–6258	B1054–62	422.4	1.9	5.1	30	10±2	<2
J1136+1551	B1133+16	1187.9	5.0	0.6	8	4±4	<4
J1243–6423	B1240–64	388.5	1.4	2.0	14	<15	<15
J1302–6350	B1259–63	47.7	0.33	0.9(1.4)	20(30)	60±8(66±7)	15±8(<7)
J1326–5859	B1323–58	478.0	2.3	1.3	17	<8	<8
J1327–6222	B1324–62	529.9	0.44		12	14±3	7±3
J1341–6220	B1338–62	193.3	0.012	0.8	12	67±4	6±4
J1359–6038	B1356–60	127.5	0.32	2.2	13	39±8	20±8
J1430–6623	B1426–66	785.4	4.5	0.6	7	11±11	<11
J1453–6413	B1449–64	179.5	1.0	1.5	10	19±10	<10
J1456–6843	B1451–68	263.4	42.5	3.4	24	<3	<3
J1522–5829	B1518–58	395.4	3.1	1.4	15	21±8	20±8
J1539–5626	B1353–56	243.4	0.80	2.3	23	39±7	10±7
J1600–5044	B1557–50	192.6	0.60	1.9	8	18±9	<9
J1602–5100	B1558–50	864.2	0.20	0.9	4	<11	<11
J1630–4733	B1627–47	576.0	0.41	2.9	20	18±5	–10±5
J1644–4559	B1641–45	455.1	0.36	2.2	16	39±1	–4±1
J1709–4429	B1706–44	102.5	0.018	5.5	32	72±3	–15±1
J1721–3532	B1718–35	280.4	0.18	1.9	17	25±1	–9±1
J1730–3350	B1727–33	139.5	0.026	0.8	12	88±16	–35±16
J1740–3015	B1737–30	606.7	0.021	0.5	8	48±4	–60±4
J1752–2806	B1749–28	562.6	1.1	0.9	12	<10	<10

The pulse profile should also narrow with increasing frequency as expected. In some profiles the components are blended together whereas in others the two components are clearly detached. The spectral index of the individual components can be varied with either leading or trailing components dominating the profile.

3.1.2 Asymmetric cone distribution

The pulsars in this category show only partial (one-sided) conal emission and no obvious core. There are two sub-types, those showing leading edge emission, generally characterised by profiles with a steep rising edge and a slower falling (inner) edge and those showing trailing edge emission where the reverse is true. Generally, rather little profile evolution is seen and there is no narrowing of the pulse width. The PA variation tends to be flat and constant over the pulse. Finally, it may be that there is emission along the magnetic meridian but which is distant (in latitude) from the pole itself. We consider this as grazing conal emission, often seen in young pulsars and characterised by a constant, but significant PA swing.

3.2 Profiles with core emission

3.2.1 Symmetric cone distribution

The pulsars in this category show ‘classic’ behaviour as a function of frequency. At low frequencies the profiles are dominated by a central component whereas at high frequencies the outrider components are well separated from the central component and dominate the profile to a greater or lesser extent.

3.2.2 Asymmetric cone distribution

In this category there is evidence for both core and cone emission in the pulse profiles with only one side of the cone visible (either trailing edge or leading edge). These pulsars show significant frequency evolution with the core reducing in prominence and the cone increasing in prominence with increasing frequency. Generally a flat PA swing is seen across the cone component with a steep swing of PA across the core component.

3.3 Young pulsars

Young pulsars appear to form their own class of pulse profiles (Qiao et al. 1995; Manchester 1996). The morphology and polarization of young pulsars in general have most recently been discussed in Johnston & Weisberg (2006). Their profiles are consistent with being conal doubles, or grazing edge cones, with little or no core emission. In virtually all cases the trailing edge of the cone dominates the profile. There is very little profile evolution as a function of frequency and the total polarization fraction remains very high at all frequencies. von Hoensbroech & Lesch (1999) showed that some pulsars in this category appear to ‘convert’ linear to circular polarization at high frequencies.

4 INDIVIDUAL PULSE PROFILES

This section details the polarization profiles of the 32 pulsars in our sample. Table 1 lists the pulsars along with their spin periods and age. Columns 5 and 6 of the table give the flux density at 8.4 GHz and the width of the profile at the 10 per cent level. The final two columns list the percentage linear and circular averaged over the profile. Note that the percentage polarization in individual components within the profile can vary significantly. Descriptions of the individual pulsars are given below and their polarization profiles shown in Figs 1 to 4.

PSR J0630–2834 (B0628–28): Observations of this pulsar show high linear polarization, modest negative circular polarization and a smooth PA swing at frequencies between 0.41 and 1.6 GHz (Gould & Lyne 1998). At 3.1 GHz the polarization fraction is significantly reduced and there is no polarization at 4.85 GHz (von Hoensbroech et al. 1998). Our 8.4 GHz observations also show no linear polarization although there is perhaps a hint of positive circular through the centre of the profile. A general narrowing of the profile is observed from low to high frequencies although the shape appears not to change. This profile is likely to be a blend of conal components without a core.

PSR J0659+1414 (B0656+14): This pulsar has very high linear polarization and significant negative circular polarization at frequencies between 0.4 and 1.64 GHz (Gould & Lyne 1998; Weisberg et al. 1999; Weisberg et al. 2004). At 3.1 GHz the polarization remains high on the trailing half of the pulse but is almost absent on the leading half. At 4.85 GHz the polarization fraction has decreased significantly and an OPM jump is visible on the leading part of the profile von Hoensbroech (1999). Our 8.4 GHz observations show that the profile has not evolved significantly and there is a complete absence of both linear and circular polarization. The pulse profile gets narrower with increasing frequency. This is one of the few examples of a young pulsar which has become depolarized at high frequencies. Its profile is perhaps a grazing conal component like that of other, similar looking young pulsars (Johnston & Weisberg 2006).

PSR J0738–4042 (B0736–40): This pulsar has a highly complex polarization pattern at 1.5 and 3.1 GHz (KJ06). There are two orthogonal mode jumps close to the rising and falling edge of the profile. At 8.4 GHz the pulsar is much less polarized than at lower frequencies. The leading component retains some linear polarization but the middle

components have only a trace remaining. The circular polarization remains low, as at lower frequencies. The orthogonal jump near the rising edge of the profile appears to be a constant feature at all frequencies. The second orthogonal jump on the trailing edge of the profile seen at low frequencies cannot be seen at 8.4 GHz due to the low fractional polarization. It seems unlikely that this pulsar contains a central core component as there is no great shape change over a wide frequency range. We consider it likely that this is in the class of symmetric conal structures with no core.

PSR J0742–2822 (B0740–28): At lower frequencies the pulsar consists of as much as seven components (Kramer 1994), of which all except the last are highly linearly polarized (KJ06). A previous observation at 8.4 GHz was made by Morris et al. (1981) and, as in our observations, the leading component now dominates the profile but the other components are still clearly visible, particularly in circular polarization. The linear polarization remains high throughout. The OPM jump seen at the trailing edge of the profile at lower frequencies cannot be discerned here due to the low linear polarization.

The frequency evolution of the profile is at odds with what one might expect. Figure 5 shows the pulse profile at 4 different frequencies. At 0.6 GHz the profile is rather asymmetric but it becomes more symmetric at 1.4, 3.1 (KJ06) and 4.9 GHz (von Hoensbroech & Xilouris 1997b). The likely interpretation of the spectral index behaviour is that the profile contains (at least) two outer conal rings with a central core components. Fits to the rotating vector model also favour this solution (Johnston et al. 2005). At 8.4 GHz however, the trailing edge has dramatically declined, contrary to expectations. The 10.6 GHz profile of Xilouris et al. (1995) shows similar features. This implies there must be a strong spectral break in the trailing components at a frequency of ~ 7 GHz.

PSR J0835–4510 (B0835–45): High time resolution observations of this pulsar show that it consists of 3 main components at frequencies above 1.4 GHz (Johnston et al. 2005). Below this frequency scattering dominates the profile shape. At 1.4 GHz the leading component dominates the profile with the trailing component rather weak. At 3.1 GHz both the middle and trailing components are bigger with respect to the initial component. At 8.4 GHz the trailing component is now dominating the profile and the leading component has become weak. Clearly then the initial component has a rather steep spectral index in contrast to the other two components. The linear polarization remains very high between 1.4 and 8.4 GHz and the circular polarization increases significantly with increasing frequency in this young pulsar. The PA swing appears to get steeper with increasing frequency. The initial component is most likely to be the core, followed by trailing edge cones with the leading cone not detected (see also Johnston et al. 2001).

PSR J0837–4135 (B0835–41): The frequency evolution of this pulsar shows ‘classical’ behaviour. At low frequencies, the central component completely dominates the profile and the linear polarization is relatively high. As one goes to higher frequencies, the conal outriders gradually become more prominent and the linear polarization declines. The circular polarization remains virtually constant over a large frequency range. The PA in the outer components is the same as that seen at lower frequencies (KJ06) but the com-

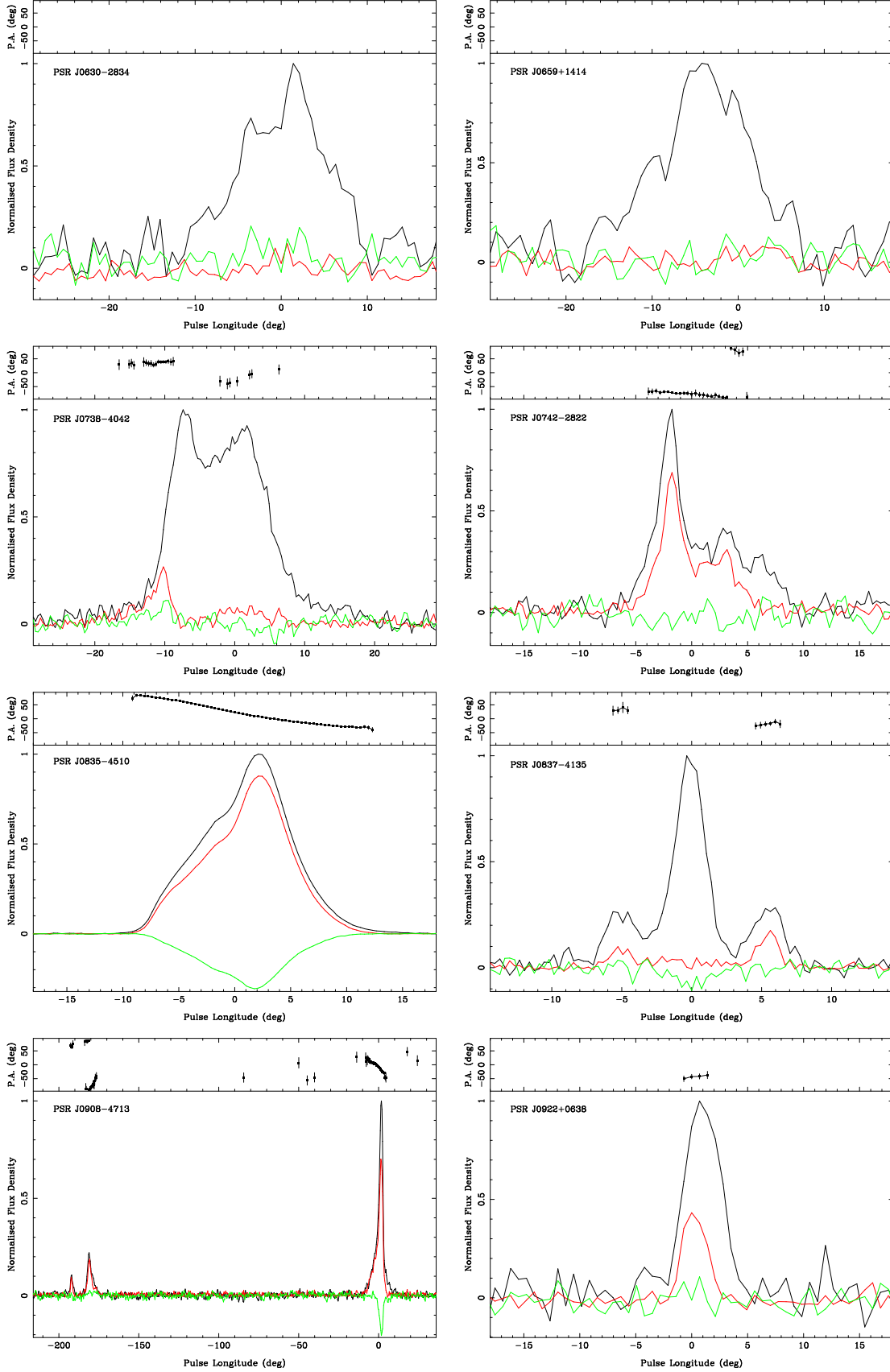


Figure 1. Polarisation profiles at 8.4 GHz for 8 pulsars as marked. The top panel of each plot shows the PA variation with respect to celestial north as a function of longitude. The PAs are corrected for RM and represent the (frequency independent) value at the pulsar. The lower panel shows the integrated profile in total intensity (thick line), linear polarization (dark grey line) and circular polarization (light grey line).

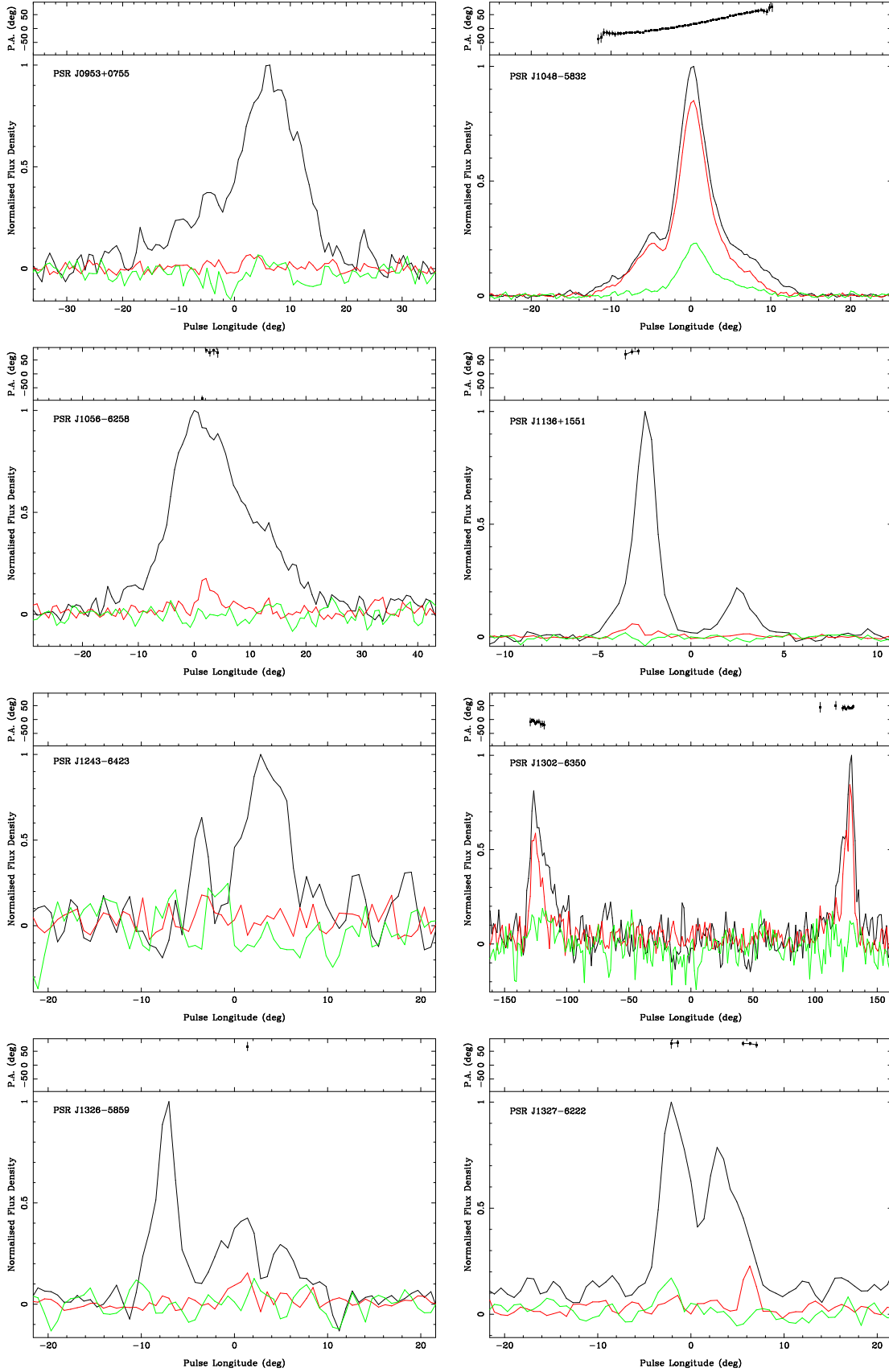


Figure 2. Polarisation profiles at 8.4 GHz for 8 pulsars as marked. See Figure 1 for details.

plex PA swing across the centre of the pulse at lower frequencies cannot be traced at this frequency. Clearly this is a symmetric profile with a central core.

PSR J0908–4913 (B0906–49): High time resolution observations of this pulsar show that both the main and interpulses consist of two components. The two components in the interpulse maintain their intensity ratio between 0.66 and 8.4 GHz. Both components are completely linearly polarized at all frequencies. In the main pulse, the two components are blended together; both are highly linearly polarized and the second component also has strong circular polarization which increases with increasing frequency. The ratio of the two components decreases with increasing frequency with the trailing component dominating the profile. This is a young pulsar and both the main and interpulses are symmetric doubles with no core as seen in other pulsars of this type (Johnston & Weisberg 2006).

PSR J0922+0638 (B0919+06): At frequencies between 0.4 and 1.6 GHz, the profile of the pulsar consists of a weak leading component and a strong trailing component which is highly linearly polarized (Gould & Lyne 1998). The total intensity profile is similar at the low frequency of 47 MHz (Phillips & Wolszczan 1992). The leading component gets weaker with increasing frequency; it is barely detectable at 3.1 GHz and not present at 4.8 GHz (von Hoensbroech & Xilouris 1997b). The linear polarization is high at all frequencies. In our 8.4 GHz observations the linear polarization has decreased and appears to have shifted towards the early part of the profile unlike at lower frequencies. This asymmetric pulse profile is likely a trailing edge cone.

PSR J0953+0755 (B0950+08): This well known pulsar has been extensively studied over a wide frequency range (see the discussion in Everett & Weisberg 2001), including frequencies as low as 25 MHz (Phillips & Wolszczan 1992). A low fraction of linear polarization is present up to 5 GHz. Unfortunately the pulsar is rather weak at 8.4 GHz and has lost virtually all its polarization. However, the overall pulse shape is similar to that at lower frequencies. The interpulse is not visible in our data, likely because of low signal to noise. Debate continues as to whether the profile is consistent with a wide double profile or whether the interpulse emission originates from a different pole to the main pulse (see Everett & Weisberg 2001). We favour the main pulse being a trailing edge cone.

PSR J1048–5832 (B1046–58): This is a young pulsar which shows two distinct components at 1.4 GHz with the leading component being highly linearly polarized and with moderate circular polarization. At 3.1 GHz the polarization remains high but the trailing component has dropped in amplitude with respect to the leading component (KJM05). At 8.4 GHz, the trailing component has virtually disappeared but now a highly polarized leading component can more clearly be discriminated than at lower frequencies. This is therefore a leading edge cone, perhaps with a core at lower frequencies.

PSR J1056–6258 (B1054–62): The linear polarization of this pulsar is relatively high at 1.4 GHz but is already in decline by 3.1 GHz (KJ06). In the current 8.4 GHz observations the polarization is virtually absent. Although the PA swings at 1.4 and 3.1 GHz are different, the lack of polarization at 8.4 GHz precludes any further comment on the

frequency behaviour. The total intensity profile looks similar to that at lower frequencies. It seems likely that this is a (leading-edge) partial cone with the magnetic pole crossing at later longitudes.

PSR J1136+1551 (B1133+16): This well known pulsar has been extensively studied over a large frequency range and shows a classic double pulse profile. At very low frequencies, the components have almost equal strength but the leading component has a significantly flatter spectral index than the trailing component and dominates at high frequencies. The linear polarization is reasonably high at 0.4 GHz but has dropped considerably at 1.4 and 4.8 GHz due to competition between orthogonal modes as revealed in the single pulse study of Karastergiou et al. (2002). In our 8.4 GHz observations, and also at 10.5 GHz (von Hoensbroech & Xilouris 1997b) a trace of polarization remains in the leading component.

PSR J1243–6423 (B1240–64): At low frequencies this profile is a simple Gaussian. The circular polarization swings through the centre of the pulse and the PA swing is also steep (van Ommen et al. 1997, KJ06). This indicates a core component. At 3.1 GHz conal outriders are starting to appear on each side of the central component (KJ06), with the leading conal component being stronger and narrower than the trailing component. At 8.4 GHz the signal to noise is low and no polarization can be seen. However, the leading conal component has increased significantly in strength compared to the central component. The trailing component however does not appear to have the same frequency evolution.

PSR J1302–6350 (B1259–63): This is the well known pulsar with a Be star companion whose total intensity profiles at a range of frequencies were most recently shown in Wang, Johnston & Manchester (2004). At 8.4 GHz the individual components are somewhat narrower than at lower frequencies. The steep rising edge and shallower decline are also consistent with lower frequencies. The degree of linear polarization remains high at 8.4 GHz, although there is a significant decrease in polarization in the inner parts of both components. The morphology and polarization of this profile are best described by a wide double (Manchester & Johnston 1995) similar to other young pulsars.

PSR J1326–5859 (B1323–56): The profile of this pulsar undergoes very strong frequency evolution. At 1.4 GHz the profile consists mainly of a strong central component with rather weak conal outriders. At 3.1 GHz the leading outrider has become significantly more prominent (KJ06). In our 8.4 GHz profile, the leading component now dominates the profile and the central component is significantly reduced. The ratio of the amplitudes of the leading and trailing component changes little between 3.1 and 8.4 GHz. The polarization is complex at low frequencies with a swing of circular polarization across the central component and a complicated PA swing (KJ06). At 8.4 GHz the polarization is almost completely absent. This is clearly a symmetrical profile with a central core.

PSR J1327–6222 (B1323–62): The profile at 8.4 GHz continues the frequency evolution seen between 1.4 and 3.1 GHz (KJ06). Whereas the trailing component is dominant at low frequencies, this has been reversed at 8.4 GHz. There is little polarization at this frequency with which to compare to the lower frequency observations. There is little

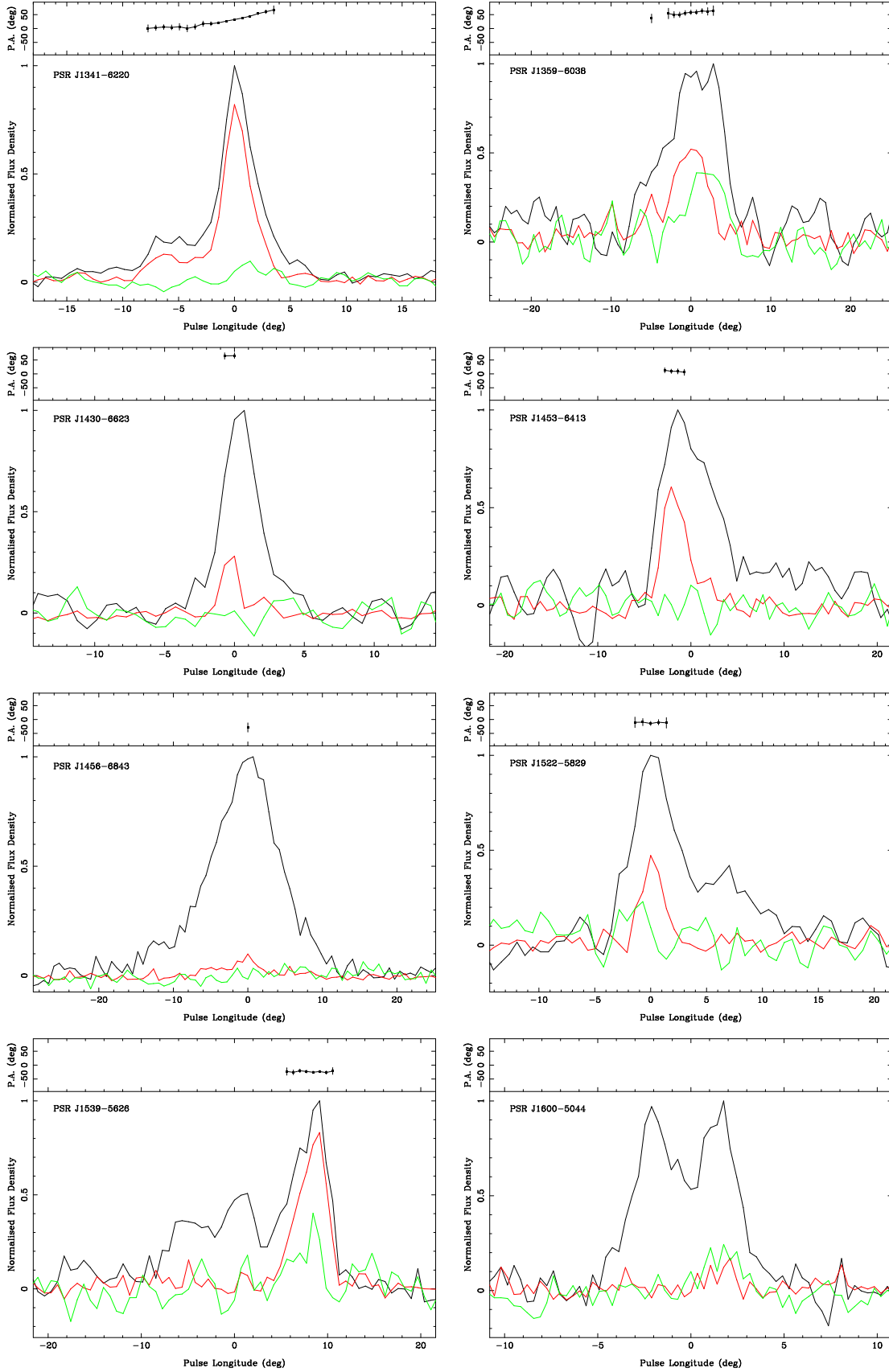


Figure 3. Polarisation profiles at 8.4 GHz for 8 pulsars as marked. See Figure 1 for details.

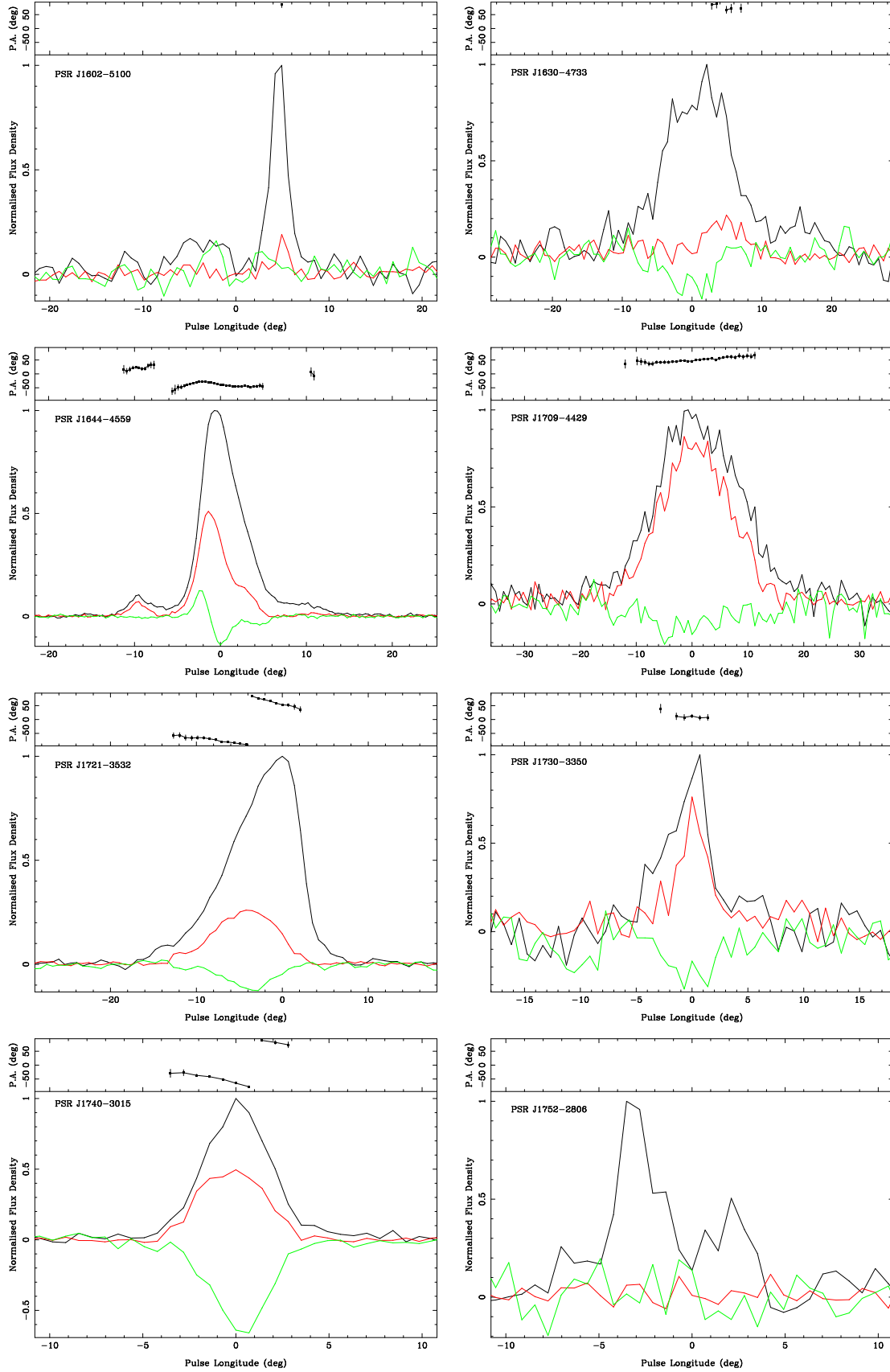


Figure 4. Polarisation profiles at 8.4 GHz for 8 pulsars as marked. See Figure 1 for details.

or no core component present, this profile is a symmetrical cone.

PSR J1341–6220 (B1338–62): This is a young pulsar which shows characteristic traits of relatively flat spectral index, a high degree of linear polarization and a double pulse profile with the trailing component dominating (Johnston & Weisberg 2006). The profile at 8.4 GHz is similar to that at 3.1 GHz with continued high linear polarization; at lower frequencies the profile is heavily scatterbroadened (Johnston & Weisberg 2006).

PSR J1359–6038 (B1356–60): At 1.4 GHz the profile appears to consist of a single component which is highly linearly polarized. At 3.1 GHz a trailing component emerges and the polarization remains high (KJ06). At 8.4 GHz the linear polarization has declined somewhat and the circular polarization has increased. A comparison between the PA swing at 3.1 and 8.4 GHz shows almost perfect agreement in the regions where there is overlap. This is most likely a leading edge conal component.

PSR J1430–6623 (B1427–66): There is considerable frequency evolution of the profile of this pulsar between 0.4 and 8.4 GHz. At frequencies of 1.4 GHz and below there is a prominent, wide leading component and a narrow dominant trailing component (Hamilton et al. 1977; Johnston et al. 2005). At 3.1 GHz the leading component is now substantially weaker. Both 1.4 and 3.1 GHz show identical and complex polarization structure. There are at least three distinct linear polarization features and the circular polarization changes sign under the narrow trailing component. The PA swing is highly complex and does not conform to the rotating vector model. In these 8.4 GHz observations the leading component is now absent and only the trailing component is detected. It retains its linear polarization and the swing of circular polarization may also still be present. This is therefore a trailing edge cone, with the core component absent at high frequencies.

PSR J1453–6413 (B1449–64): There is substantial evolution of the profile of this pulsar between 0.6 and 8.4 GHz. At 0.6 GHz the profile consists of a simple Gaussian component with moderate polarization and a steep swing of position angle (McCulloch et al. 1978). At 1.4 GHz, a small leading component appears which is highly polarized and the dominant trailing component has moderate polarization orthogonal to the leading component. There is also a highly extended tail which has a further orthogonal jump (Johnston et al. 2005). At 3.1 GHz the leading component is now about as dominant as the trailing component, there are no orthogonal jumps and the extended tail is still present. In these 8.4 GHz observations, the leading component entirely dominates the profile and remains highly polarized. There is still a hint of an extended tail to the profile. This is best explained by a leading edge cone plus weak core component.

PSR J1456–6843 (B1451–68): The properties of this pulsar’s profile between 0.17 and 1.6 GHz have been extensively described in Wu et al. (1998). At the very lowest frequencies the pulsar has a clear core component with two conal outriders. At higher frequencies the pulse shape is much more amorphous and Wu et al. (1998) argue that it has five blended components. The pulse profile shows rather little evolution with frequency above 1.4 GHz. The small amount of polarization seen at this frequency has almost entirely disappeared at 8.4 GHz. There is a significant nar-

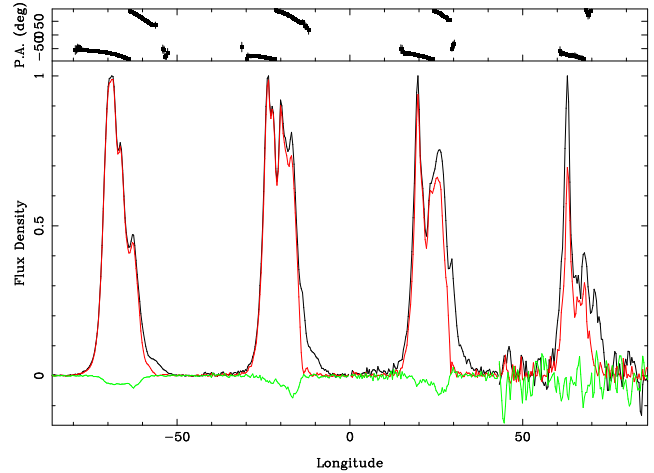


Figure 5. PSR J0742–2822 at 0.66 GHz (extreme left), 1.4 GHz (middle left), 3.1 GHz (middle right) and 8.4 GHz (extreme right) in full polarization. Note the dramatic changes in the total intensity profiles as a function of frequency and the high linear polarization at all frequencies.

rowing of the profile, with the pulse width at 8.4 GHz being about half that at 1.4 GHz. Following Wu et al. (1998) therefore, it seems as if the outer conal components (which have a steep spectral index) have now disappeared at 8.4 GHz entirely. It is also possible that the core emission is now much weaker at this frequency, and the resultant (narrow) profile is a blend of the two inner conal components.

PSR J1522–5829 (B1518–58): The 1.4 GHz profile shows a simple Gaussian which likely consists of two equal strength components as seen in the linear polarization profile (Qiao et al. 1995). At 3.1 GHz the leading component is starting to dominate the profile and this component is more highly polarized than its counterpart at 1.4 GHz (KJM05). At 8.4 GHz the leading component now dominates the profile, still has a high degree of linear polarization and the same flat PA swing. It is difficult to tell whether this is simply a leading edge conal profile or a symmetrical cone with a steep spectral index on its trailing edge.

PSR J1539–5626 (B1535–56): At 1.4 GHz, the profile of the pulsar appears to consist of a simple Gaussian (Qiao et al. 1995) albeit at low time resolution. However linear polarization is only seen on the trailing half of the component, indicating that there is a blend of at least two components. At 3.1 GHz, three components are seen; a broad leading component, a narrow central component and a highly polarized narrow trailing component (KJM05). In our 8.4 GHz data, three components are also present but the trailing component now dominates and remains highly polarized. This pulsar therefore has a core component flanked by conal outriders although again the outriders have very different spectral index (and polarization) behaviour.

PSR J1600–5044 (B1557–50): At frequencies below 1 GHz the pulse profile is scatter broadened and not much structure can be discerned (van Ommen et al. 1997). At 1.56 GHz the profile shows two blended components with the trailing component showing moderate linear polarization and very strong positive circular polarization (Wu et al. 1993). At 3.1 GHz the two components are more clearly split with the trailing component again having circular polariza-

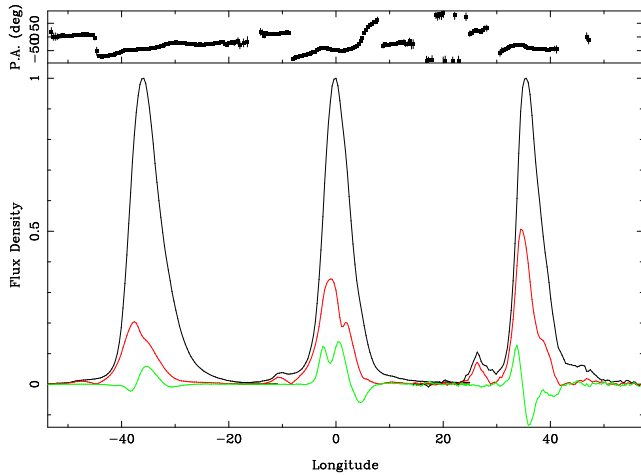


Figure 6. PSR 1644–4559 at 1.4 GHz (left), 3.1 GHz (middle) and 8.4 GHz (right) in full polarization. The pulse profile does not evolve strongly with frequency although outliers are more prominent at the highest frequency. Note the increasing linear polarization and the peculiar evolution of the circular polarization.

tion in excess of 50 per cent. The PA swing appears much steeper at 3.1 GHz than at 1.6 GHz. In our 8.4 GHz observations the ratio of the two peaks is similar to that at the lower frequencies. However both the linear and circular polarization have significantly decreased. This is a symmetric pulse profile with no core.

PSR J1602–5100 (B1558–50): The profile of this pulsar undergoes significant frequency evolution. At 0.95 GHz there are two components with the leading component dominating. At 1.4 GHz the profile is not greatly different (KJ06). A steep swing of PA over more than 200° is seen through the centre of the pulsar and there is also a swing of circular polarization from negative to positive. At 3.1 GHz, the ratio of the amplitudes of the components is reduced. This evolution appears to accelerate because in our 8.4 GHz profile there remains only the merest hint of the leading component and the trailing component completely dominates the profile. This therefore appears to be a symmetrical double with no core emission and an asymmetric spectral index for the two components.

PSR J1630–4733 (B1627–47): Scatter broadening dominates the profile at low frequencies, but at 3.1 GHz the pulse shape is a simple Gaussian, as is the circular polarization although there are two distinct linear polarization features (KJM05). In our 8.4 GHz profile the pulse shape is similar to that at 3.1 GHz although the linear polarization is present only on the trailing half and the profile appears somewhat narrower. This is therefore a blended symmetrical double.

PSR J1644–4559 (B1641–45): At 1.4 GHz the pulse profile consists of 4 components with a small leading component and blend of components within the main pulse. The circular polarization swings from negative to positive near the pulse centre (Johnston 2004). At 3.1 GHz the profile looks similar except that the small leading component is starting to become more prominent. However, the fractional linear polarization has increased and the circular polarization is very different. The PA variation with pulse longitude is complex and different between the two frequencies (KJ06). At 8.4 GHz the profile looks similar with the trailing compo-

nent being relatively brighter and a small trailing component starting to appear. The linear fraction continues to increase at least on the leading part of the pulse. The orthogonal jump in PA after the leading component is at the same longitude at all frequencies. The circular polarization is again different from either of the two lower frequencies. Figure 6 shows the polarization profiles of the pulsar at three frequencies. The profile is consistent with a leading edge cone.

PSR J1709–4429 (B1706–44): This pulsar is a young pulsar with a characteristic simple profile, high degree of linear polarization and a rather flat PA swing (Johnston & Weisberg 2006). At 8.4 GHz its total intensity profile is virtually unchanged relative to that at lower frequencies. The linear polarization remains high and there is moderate circular polarization. It seems likely that this is a grazing edge cone. This pulsar is the brightest in our sample at 8.4 GHz with a flux density not significantly different to that at 1.4 GHz.

PSR J1721–3532 (B1718–35): The profile of this pulsar appears to be similar between 1.4 and 8.4 GHz (Qiao et al. 1995; KJM05) although the lower frequency has a long scattering tail. There is a slow rising edge to the profile followed by a steep falling edge. Moderate linear and right-hand circular polarization is present at all these frequencies. This is likely to be a trailing edge cone.

PSR J1730–3350 (B1727–33): The profile of this young pulsar at 8.4 GHz is highly linearly polarized despite the low signal to noise ratio. Some right-hand circular polarization is also seen. A comparison to an earlier observation at 1.4 GHz (Crawford et al. 2001) reveals little change in the fractional polarization between these two frequencies. The PA of the linear polarization is flat, both at 1.4 and 8.4 GHz. This is a typical young pulsar profile, likely a grazing edge cone.

PSR J1740–3015 (B1737–30): At all frequencies, the profile is simple and the total polarization is high. The fractional linear and circular polarization increases between 0.4 and 1.4 GHz (Gould & Lyne 1998). This pulsar retains a very high degree of polarization at 4.8 GHz (von Hoensbroech et al. 1998) and in our 8.4 GHz profile with 51% linear and 60% circular polarization. The PA swing is the same at all frequencies. This pulsar is a virtual twin of PSR B0144+59 which shows a very similar evolution with frequency (von Hoensbroech et al. 1998). Again, this is a typical young pulsar profile, likely a grazing edge cone.

PSR J1752–2806 (B1749–28): At frequencies below 1.4 GHz the pulse profile looks very similar and consists of two blended components (van Ommen et al. 1997, KJ06). At 3.1 GHz the profile has significantly narrowed and the trailing component is strongly reduced in amplitude (KJ06). The PA swing is complex at different at 1.4 GHz and 3.1 GHz. Our 8.4 GHz observations show that the initial leading component has continued to narrow. However, a strong trailing component has now emerged at significantly later longitudes than the component seen at low frequencies (and which may also be present in the 4.7 GHz observation of Sieber et al. 1975). There is virtually no polarization at this frequency. It seems likely that this is still a core dominated profile with a trailing conal component.

Table 2. Pulsar classification. The three columns following the name indicate whether the leading (l), central (c) and trailing (t) components are polarized with f denoting flatter spectrum. Young pulsars are listed first in their respective categories.

Profiles with cores		l	c	t	
Symmetric					
J0742–2822	B0738–28	•f	•	•	young
J0837–4135	B0835–41			•	
J1243–6423	B1240–64				
J1326–5859	B1323–58	f			
J1456–6843	B1451–68				
J1539–5626	B1535–56			•f	
Asymmetric					
J0835–4510	B0833–45		•	•	young
J1430–6623	B1426–66			•	
J1453–6413	B1449–64	•			
J1752–2806	B1749–28				
Profiles without cores		l	c	t	
Symmetric					
J0659+1414	B0656+14				young
J0908–4913	B0906–49	•		•	young
J1302–6350	B1259–63	•		•	young
J1341–6220	B1338–62	•		•	young
J0630–2834	B0628–26				
J0738–4042	B0736–40				
J1136+1551	B1133+16	f			
J1327–6222	B1324–62	f			
J1522–5829	B1518–58	•f			
J1600–5044	B1557–50				
J1602–5100	B1558–50			f	
J1630–4733	B1627–47				
Asymmetric					
J1048–5832	B1046–58		•		young
J1709–4429	B1706–44		•		young
J1730–3350	B1727–33		•		young
J1740–3015	B1737–30		•		young
J0922+0638	B0919+06			•	
J0953+0755	B0950+08				
J1056–6258	B1054–62	•			
J1359–6038	B1356–60	•			
J1644–4559	B1641–45	•			
J1721–3532	B1718–35			•	

5 DISCUSSION

We can make several general observations about polarization at 8.4 GHz, reinforcing the conclusions come to by others. First, the general fractional polarization is lower at high frequencies than at low frequencies, apart from in the young pulsars. Secondly, it is clear that conal emission generally has a flatter spectral index than the core emission and hence the cones become much more prominent at this frequency. Thirdly, the overall profile width does not greatly decrease between 1.4 and 8.4 GHz; the general effect of width evolution is only really visible below about 600 MHz. One might expect that the PA swing at high frequencies becomes simpler without the distorting influence of the central component(s). Unfortunately this inference is not obvious because of the overall lack of polarization in the profiles.

Table 2 shows the classification of the pulsars in tabular

form according to the scheme laid out in Section 3. Three aspects can be clearly identified:

(i) The young pulsars all show a very high degree of polarization, the only exception being PSR J0659+1414 which abruptly depolarizes at frequencies above about 4 GHz. This result confirms the results found by von Hoensbroech et al. (1998) who showed a correlation between the polarized fraction and age. The polarized fraction remains approximately constant with frequency although in some pulsars (e.g. Vela) the linear polarization decreases while the circular polarization increases.

(ii) Core emission is generally lacking in young pulsars although there are some exceptions. Johnston & Weisberg (2006) comment extensively on the pulse morphology of young pulsars. In those pulsars which do show core emission at 8.4 GHz, virtually all lack polarization.

(iii) The pulsars with asymmetric cones tend to be relatively highly polarized whether they are leading or trailing edge. In contrast, the symmetrical profiles have virtually no polarization. This is a rather surprising result, and lends itself to no obvious explanation.

In young pulsars the emission height is large even at high frequencies (Johnston & Weisberg 2006) and the emission remains polarized. In contrast core emission in older pulsars arises from low in the magnetosphere (Mitra & Rankin 2002) and quickly becomes less polarized with frequency. Pulsars with a symmetrical conal configuration, likely to be true conal rings, also appear to have low emission heights (Gupta & Gangadhara 2003) and are also observed to show little or no polarization at high frequencies. We therefore surmise that the fractional polarization is determined by the emission height. Perhaps then the asymmetric profiles are more symbolic of the patchy beam model (Lyne & Manchester 1988) with conditions necessary for the production of radio emission occurring higher in the magnetosphere.

In KJM05 we outlined a simple model whereby the various evolutionary features of polarized components could be explained in the context of the spectral index behaviour of the competing orthogonal modes. Three types of behaviour are expected. In the first, the polarization is high at all but very low frequencies and the spectral index is shallow, in the second the polarization declines as a function of frequency up to at least 10 GHz and the spectral index is steep. In the third, the polarization fraction declines and then increases again with a minimum in the GHz observing bands and one might also expect a spectral break in the data. All three of these types are seen in the 8.4 GHz profiles. The young pulsars which are highly polarized at low frequencies remain so at high frequencies and their spectral indices are reasonably flat (type 1 behaviour). Furthermore, individual highly polarized components such as that seen on the trailing edge of PSR J1539–5625 remain highly polarized and begin to dominate the profile at high frequencies because of their flat spectral index. Type 2 behaviour is most common, with declining polarization seen in the majority of the non-young pulsars. Finally type 3 behaviour is clearly seen in PSR J1644–4559 with the polarization fraction increasing between 1.4 and 8.4 GHz (see fig 6).

Highly polarized, type 1 components can account for the profiles of young pulsars. However, highly polarized compo-

nents are also often found in conjunction with other, less polarized components within individual profiles. These are extremely interesting cases, in that the highly polarized component may originate from higher in the magnetosphere than the rest of the profile. Type 2 components are compatible with the standard model, where higher frequencies originate from lower heights and therefore are also less polarized. Type 3 are more complicated to explain in the context of emission heights. Two possibilities exist. Either the higher frequencies originate from low emission heights as the standard model suggests, and the high polarization is set by some other mechanism, or the components that are more polarized with frequency originate further from the pulsar surface, contrary to the standard behaviour. In this context it would be useful to devise a technique to measure the emission heights of such components in an independent way (e.g. Gangadhara 2005). The tentative conclusion about the fractional polarization and emission height that we have reached here could be strengthened or challenged by theoretical considerations. It is certainly tempting to start drawing conclusions suggesting a different altitude of emission of various components within a single profile. The impact of this on observational parameters such as the component widths and the PA may provide interpretation to the most complex observations (Karastergiou & Johnston 2006), which do not adhere to the standard pulsar model.

A physical model in a series of papers by Petrova (2001, 2002, 2003) attempts to explain the observed features of pulsar polarization in terms of orthogonal mode conversion and refraction in the magnetosphere. In her model, a single emission mode is produced which is later converted into two orthogonal modes. This conversion best occurs in regions of longitudinal propagation with respect to the magnetic field. In turn, these regions occur where refraction is strongest. At high frequencies (or low emission heights more strictly) refraction is effective, and therefore mode conversion depolarizes the observed emission. Again, the high altitude of the emission from young pulsars shields them from this effect and the little mode conversion happens. This is also supported by the relatively simple swing of the PA traverse in young pulsars.

6 CONCLUSIONS

We have substantially increased the number of pulsars with high frequency data by producing calibrated polarization profiles for 32 objects. Many of the features seen and the evolution of the profiles from low to high frequency are generally as expected in the standard picture of the observational phenomenology. Of most interest is the continued high polarization fraction seen in the young pulsar profiles and the curious result that asymmetric conal features are more highly polarized than the symmetric features. The observations point towards the fractional polarization being related to the emission height, with polarized components originating from higher in the magnetosphere. It is heartening that the recent theoretical models of Petrova and others go some way towards explaining the diversity of features seen.

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REFERENCES

- Crawford F., Manchester R. N., Kaspi V. M., 2001, *AJ*, 122, 2001
- Everett J. E., Weisberg J. M., 2001, *ApJ*, 553, 341
- Gangadhara R. T., 2005, *ApJ*, 628, 923
- Gould D. M., Lyne A. G., 1998, *MNRAS*, 301, 235
- Gupta Y., Gangadhara R. T., 2003, *ApJ*, 584, 418
- Hamilton P. A., McCulloch P. M., Ables J. G., Komesaroff M. M., 1977, *MNRAS*, 180, 1
- Hotan A. W., van Straten W., Manchester R. N., 2004, *PASA*, 21, 302
- Johnston S., 2004, *MNRAS*, 348, 1229
- Johnston S., Hobbs G., Vigeland S., Kramer M., Weisberg J. M., Lyne A. G., 2005, *MNRAS*, 364, 1397
- Johnston S., van Straten W., Kramer M., Bailes M., 2001, *ApJ*, 549, L101
- Johnston S., Weisberg J. M., 2006, *MNRAS*, In Press
- Karastergiou A., Johnston S., 2006, *MNRAS*, 365, 353 (KJ06)
- Karastergiou A., Johnston S., Manchester R. N., 2005, *MNRAS*, 359, 481 (KJM05)
- Karastergiou A., Johnston S., Mitra D., van Leeuwen A. G. J., Edwards R. T., 2003, *MNRAS*, 344, L69
- Karastergiou A., Kramer M., Johnston S., Lyne A. G., Bhat N. D. R., Gupta Y., 2002, *A&A*, 391, 247
- Karastergiou A., von Hoensbroech A., Kramer M., Lorimer D., Lyne A., Doroshenko O., Jessner A., Jordan A., Wielebinski R., 2001, *A&A*, 379, 270
- Kramer M., 1994, *A&AS*, 107, 527
- Kramer M., Karastergiou A., Gupta Y., Johnston S., Bhat N. D. R., Lyne A. G., 2003, *A&A*, 407, 655
- Kramer M., Wielebinski R., Jessner A., Gil J. A., Seiradakis J. H., 1994, *A&AS*, 107, 515
- Lyne A. G., Manchester R. N., 1988, *MNRAS*, 234, 477
- McCulloch P. M., Hamilton P. A., Manchester R. N., Ables J. G., 1978, *MNRAS*, 183, 645
- Manchester R. N., 1996, in Johnston S., Walker M. A., Bailes M., eds, *Pulsars: Problems and Progress*, IAU Colloquium 160. Astronomical Society of the Pacific, San Francisco, pp 193–196
- Manchester R. N., Johnston S., 1995, *ApJ*, 441, L65
- Mitra D., Rankin J. M., 2002, *ApJ*, 577, 322
- Morris D., Graham D. A., Seiber W., Bartel N., Thomasson P., 1981, *A&AS*, 46, 421
- Petrova S. A., 2001, *A&A*, 378, 883
- Petrova S. A., 2002, *A&A*, 383, 1067
- Petrova S. A., 2003, *A&A*, 408, 1057
- Phillips J. A., Wolszczan A., 1992, *ApJ*, 385, 273
- Qiao G. J., Manchester R. N., Lyne A. G., Gould D. M., 1995, *MNRAS*, 274, 572
- Rankin J. M., 1983, *ApJ*, 274, 333
- Rankin J. M., 1990, *ApJ*, 352, 247
- Siebert W., 1997, *A&A*, 321, 519

- Sieber W., Reinecke R., Wielebinski R., 1975, *A&A*, 38, 169
- van Ommen T. D., D'Alessandro F. D., Hamilton P. A., McCulloch P. M., 1997, *MNRAS*, 287, 307
- von Hoensbroech A., 1999, PhD thesis, University of Bonn
- von Hoensbroech A., Kijak J., Krawczyk A., 1998, *A&A*, 334, 571
- von Hoensbroech A., Lesch H., 1999, *A&A*, 342, L57
- von Hoensbroech A., Xilouris K. M., 1997a, *A&A*, 324, 981
- von Hoensbroech A., Xilouris K. M., 1997b, *A&AS*, 126, 121
- Wang N., Johnston S., Manchester R. N., 2004, *MNRAS*, 351, 599
- Weisberg J. M., Cordes J. M., Kuan B., Devine K. E., Green J. T., Backer D. C., 2004, *ApJS*, 150, 317
- Weisberg J. M., Cordes J. M., Lundgren S. C., Dawson B. R., Despotes J. T., Morgan J. J., Weitz K. A., Zink E. C., Backer D. C., 1999, *ApJS*, 121, 171
- Wu X., Gao X., Rankin J. M., Xu W., Malofeev V. M., 1998, *AJ*, 116, 1984
- Wu X., Manchester R. N., Lyne A. G., Qiao G., 1993, *MNRAS*, 261, 630
- Xilouris K. M., Kramer M., Jessner A., Wielebinski R., Timofeev M., 1996, *A&A*, 309, 481
- Xilouris K. M., Seiradakis J. H., Gil J. A., Sieber W., Wielebinski R., 1995, *A&A*, 293, 153